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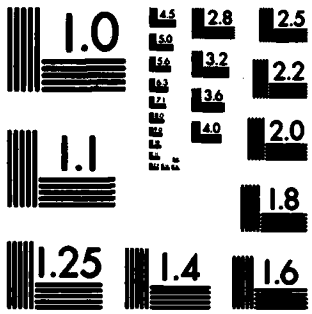
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# AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD REPORT No.727

# Design of Bolted Joints in Composites



NORTH ATLANTIC TREATY ORGANIZATION

AGARD-R-727

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.727

# DESIGN OF BOLTED JOINTS IN COMPOSITES

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# PREFACE

The rapidly increasing application of composite structures on NATO Military Systems has intensified interest in development of strength and life analysis methods for mechanically fastened composite joints. A number of NATO country programs have developed an extensive data base on strength and life, and identified a wide range of additional needed data, procedures and design requirements.

An ad-hoc Group of the Structures and Materials Panel has been formed to study and define an activity aimed to improve the understanding of static and fatigue behaviour of mechanically fastened composite joints.

Following discussion at the 58th meeting in Spring '84 in Siena, Italy, Pilot Papers were invited to review the state of the knowledge on strength and life data of composite joints. One of these Pilot Papers, by Mr P.Lafon (FR), was presented at the 59th meeting in Fall '84 in Toulouse, France, and three others, respectively by Dr D.Schütz, Mr R.W.West and Dr G.P.Sendeckyj, at the 60th meeting in Spring '85 in San Antonio, USA.

All these Pilot Papers were very useful in helping the decision to form a Sub-committee to develop a Specialists' Meeting that will be held in Spring '87; they were judged of great interest, and it was therefore decided that they should be published as an AGARD document.

V.Giavotto
Chairman
Sub-Committee on
Mechanically Fastened Joints
in Composites

## CONTENTS

# STRENGTH-BEHAVIOUR OF CARBON FIBER REINFORCED PLASTIC JOINTS

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## SUMMARY

High strength fiber reinforced plastic aircraft structures are still - as metal structure - jointed by shear loaded fasteners. This structural detail is very strength critical in carbon fiber reinforced plastic structures due to the high notch sensitivity of this material.

A short survey will be given, on the strength and deformation behaviour of CFRP joints under static and repeated loading. Furtheron the most essential detail design and manufatoring parameters will be discussed and finally the possibilities to improve the strength behaviour of CFRP joints will be discussed.

## STRENGTH AND DEFORMATION BEHAVIOUR OF CFRP JOINTS

Fig. 1 schows the static and fatigue strength of unnotched, notched and jointed CFRP in the form of SN-lines. The two different jointed specimen have a load transfer of 50 and 100 per cent respectively. The 100 per cent load transfer joints have naturally a higher notch severity, than the 50 per cent joints. The figure shows the well known fact that notch sensitivity of CFRP is highest at the static strength and low cycle fatigue loading whereas the SN-lines of the different notch serverities are closer to each other in the region of the higher lifes. From the lower slope of the SN-lines it can be concluded that a composites joint which is properly designed for static loadings is not fatigue critical in most cases.

The fatigue life of a joint might not end only by total failure but also by a loss of stiffness due to the repeated loads which is not permissible for that special application. The stiffness of a composite joint is goverend by the movement of the two jointed parts relative to each other. Fig. 2 shows load-relative movement hystereses of a CFRP joint in dependence of the number of endured load cycles. The relative movement of the two jointed parts increases over the full range of cycles. Comparing this behaviour with that of a similar joint of aluminum sheets shows some differences see fig. 3.

There is a very rapid change in stiffness at the first fatigue cycles towards greater stiffness and than a stable behaviour over a very long period of the total live. For that reason the failure criterion for composite joints will be in most cases not total failure but unpermissible loss of stiffness. A comparison of stiffness changes of different structural details of CFRP is shown on fig. 5. The specimen used for this investigation are shown on fig. 4. The laminate build-up for the unnotched, noched (by a bore), unloaded hole filled by a fastener and single and a double shear joint with load transfer specimen was the same. The figure shows the increase of deformation or relative movement over the percentage of life to failure. With the double shear joint you see the allready mentioned steady decrease over the full life. Very striking is the fast increase of relative movement of the single shear joint. The tilting of the bolt gives a very unfavourable distribution of bearing stresses, which results in the destruction of the bearing surface and an ovalisation of the hole.

## INFLUENCE OF VARIOUS DESIGN AND MANUFACTURING PARAMETERS

Fig. 6 gives a survey on the influence of various design and manufacturing parameters on the three strength criteria static strength, fatigue strength and deformation behaviour of composite joints. A very beneficial influence on all the three strength criteria has an interference fit of the fastener. The mechanismes which result in this improvement are the same as know since a long time with metal joints. The interference fit reduces the amplitude of local stresses and strains at the border of the bore. An increase of the fastener clamping is also very beneficial. This comes from two mechanisms: first it increases the amount of load transfer by friction and reduces therefore the bearing stresses, secondly the clamping force of the fastener retards the delamination progress by just reducing the possibility of the laminate to "breath". Local reinforcements and softening or tailoring are discussed later on in our presentation more in detail. There is not too much known about the influence of environment on CFRP joints. This is especially true for environmental influences with service-like frequently changing temperatures. The result of different investigations are, due to the many influencing parameters contradicting, see fig. 7. The content of the figure is not discussed therefore in detail.

An example is shown on fig. 8 where a very detrimental influence of moisture can be seen; probably the most detrimental influence is due to the lower frictional coeficient when water is present between the jointed surfaces. The detrimental influence is especially high in the high cycle part of the SN-line. If a composite joint made of the presently used Carbon-fiber-Epoxy materials, is designed proberly for the static load cases it will withstand in most cases also the fatigue loadings in relation to the two failure criteria: residual strength after fatigue loading and decrease of stiffness.

This is not so much the fact because of a good fatigue behaviour but of a very bad static strength resulting from the brittleness of the material combined with the high stress concentrations in a bolted joint. For higher permissible stresses therefore the local stresses and the notch sensitivity of the material should be reduced. This can be achieved by local reinforcements, by a tailored laminate build-up in the region of the load transfer of the shear loaded fasteners or by high elongation fibers and matrix materials.

## LOCAL REINFORCEMENT

At our Institute an extensive investigation on the possibilities of local reinforcements has been performed. Fig. 9 shows the specimen for a part of the investigation. It was a double shear joint with one or two fasteners resulting in 100 % respectively 50 % load transfer. The strength behaviour of the reinforced specimen was compared with a normal specimen. The laminate build-up of the reinforcements, was the same as for the basic material. In taking such measures it is essential to look to all possible weak points of this detail design, because there are new ones for example at the end of the reinforcements. For that reason the reinforcement is done in two steps in the central part. Fig. 10 shows the a typical result of some static strength tests in tension and compression for the specimen equiped with only one fastener. The parameter "torque moment" of the fastener is varied as you might see between 11 and 2,9 Nm. The result compares the static strength of the basic specimen with that of the reinforced one.

The reinforcement was in this case nearly by a factor of 1.5 in area. Though the improvement is remarkable it does not reach this factor of 1.5 which would be an ideal result. This is probable resulting from the bolt bending. The static strength of the undisturbed area of the specimen could not be reached by far.

In a NASA investigation see fig. 11 an extreme reinforcement by a factor of 4 was tested. This reinforcement was bonded or cocured to the basic material. The results of the static tests are shown on a relative scale related to the static strength of the unnotched material. As can be seen the strength of the unnotched material nearly could be reached with the cocured version. The first column shows the strength of a basic specimen without reinforcement for comparison. A tremendous improvement could be reached. It is essential to mention that the failure mechanisme was through detachement of the reinforcement and the final failure of the net section was secondary. In practical cases a reinforcement by a factor of four will be not possible in most cases but it is interesting to know that you can nearly reach the static strength of the unnotched material by reinforcements.

Tailoring means the adaption of the laminate build-up to the flow of forces. In a field of load transferring fasteners the design of the laminate is made in a way to reduce the peak stress concentrations. A practical example is shown in fig. 12. A load introducing from a metall part into a CFRP sheet is shown. The CFRP is build-up of two different regions; one has only $\pm$ 45$^{\circ}$ C fibers and is by that not very stiff in the load introduction direction the other has a mixture of 0$^{\circ}$ and $\pm$ 45 degree fibers.

In comparing test results with a basic specimen which had not this mixture of different laminate lay-ups an improvement in strength behaviour was reached in the order of a factor of two.

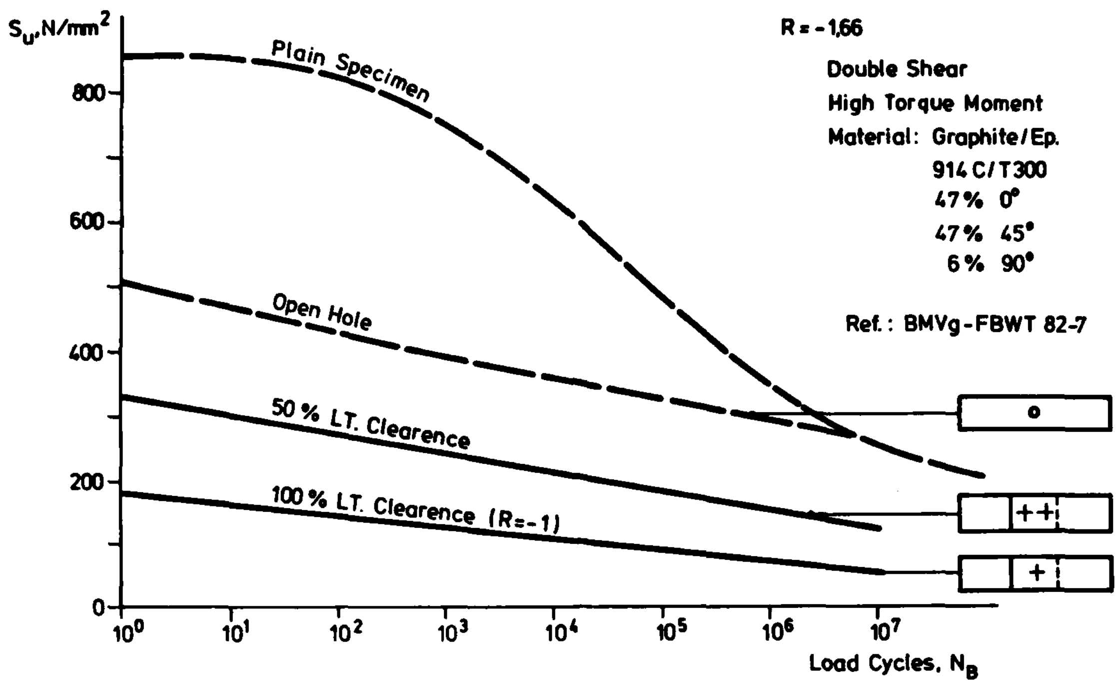
When relating this result to the weight there is still the very remarkable improvement of 25 %. In the following an attempt is made to explain the reasons for that improvement, see fig. 13. Imagine a joint where three fasteners or rows of fasteners are in the direction of the load. In a conventional joint the load transferred by the first two bolts passes the hole for the third bolt. Thus the local stresses around this third hole are the superposition of the stresses from these bypassing loads plus the stresses from the load transfer at this hole itself. In the special joint, we are speaking of the transferred loads can not flow in the $\pm$ 45$^{\circ}$ laminate because it is not rigid in the load direction so these loads flow directly by shear stresses to the outer part of the joint where the 0$^{\circ}$ fibers are stiff in the load direction. By this mechanisme the critical third hole has nearly no bypassing loads and stresses. In the special example only one tenth of the bypassing loads stays in the middle $\pm$ 45$^{\circ}$ soft region. Another beneficial mechanisme is that the distribution of the total load to be transferred from one part to another in a field of fasteners is more uniform because of a more flexible bearing surface in a $\pm$ 45$^{\circ}$ laminate. There is a third beneficial mechanisme which refers to the local flow of the transfered load, see fig. 14. If you compare the strength of $\pm$ 45$^{\circ}$ specimen where load is transferred via a bolt hole and the reacting load is in tension in one case and in shear in the other case you will find the very high improvement by a factor of two in favour of the shear reacting load.

All the described three mechanismes help to improve the strength of the tailored specimen. In many cases a reinforcement or tailoring might not be feasable but never the less in jointing of composites something most be done to improve the static strength.

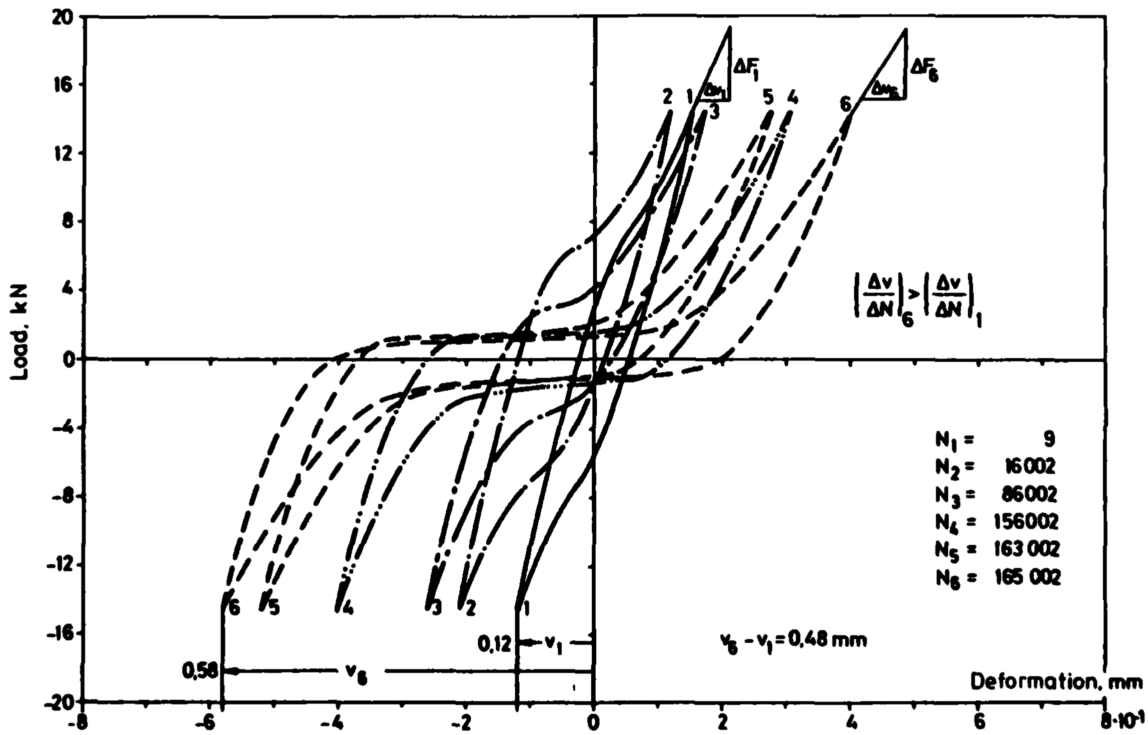
## CONCLUSIONS

The reason that mechanically jointed composite are not very fatigue critical up to now is not so much that they are very good in fatigue. The reason is rather that they are so very bad in static strength. In other words: as soon as the static strength is improved the problem of fatigue strength will show up again.

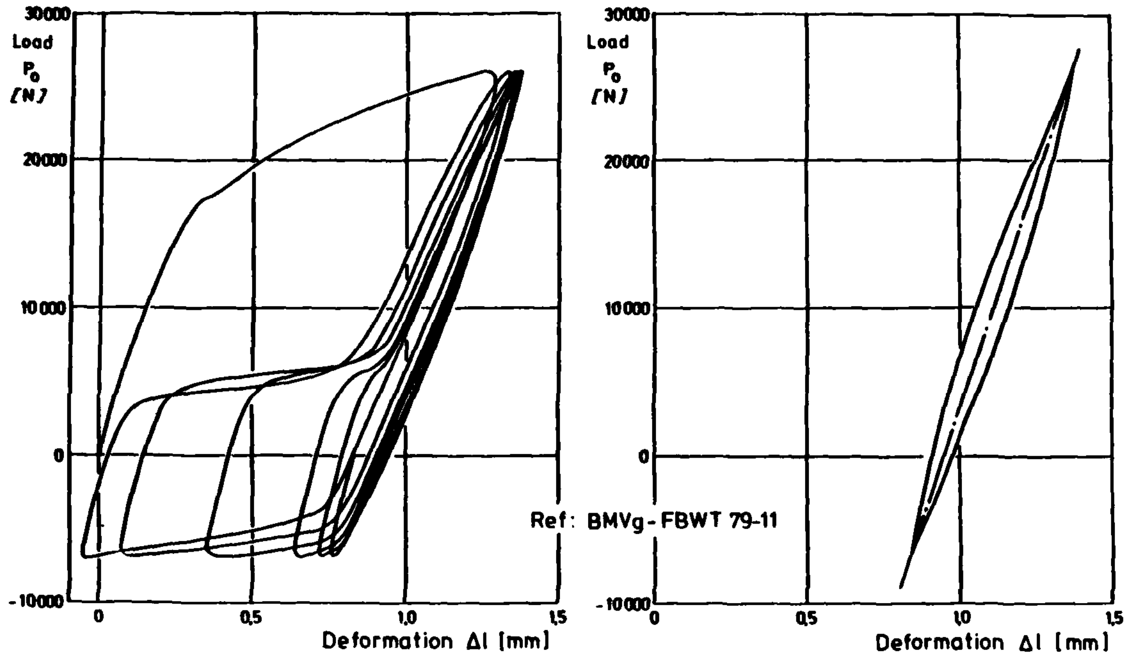
So the problem of mechanical strength of composite joints has to be evaluated in connection as well with the development tendencies in fibers and matrix materials as also in connection with the possibilities to design with more complex laminate build-ups or hybrid composites. The knowledge of the environmental sensitivity of composites has to be improved urgently.




**SN-Lines of CFRP Joints in Comparison to SN-Lines of Plain and Notched Specimens** Fig. 1



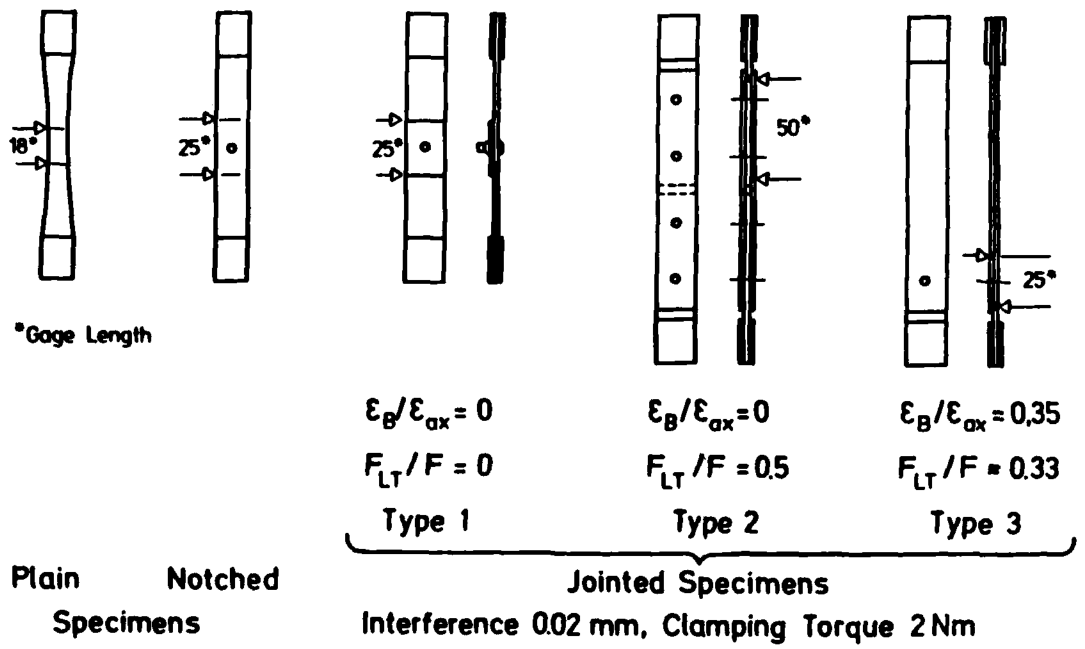

**Load – Deformation – Behaviour of a CFRP-Joint 100% Load Transfer** Fig. 2



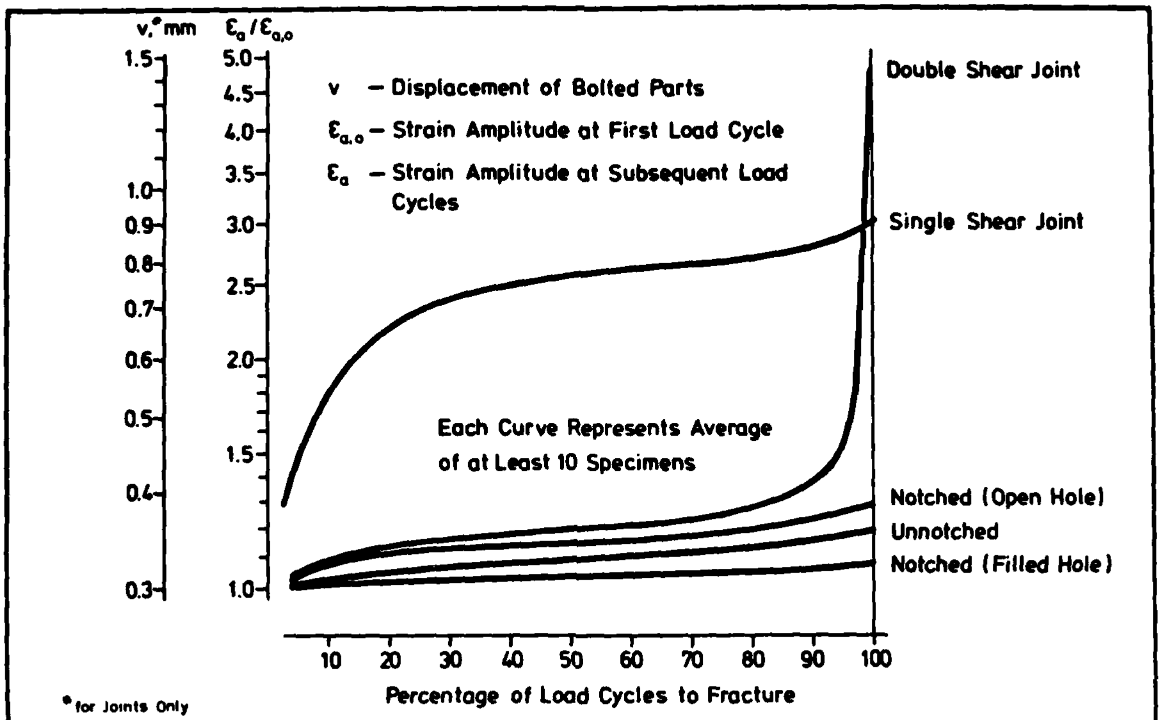

Hysteresis Curves 1 to 6 Hysteresis Curves 27 to 29 (Stabilized)

Aluminium Alloy 7075-T6

Clearence Fit, 100 % Load Transfer Fig. 3




CFRP Fatigue Specimen Fig. 4



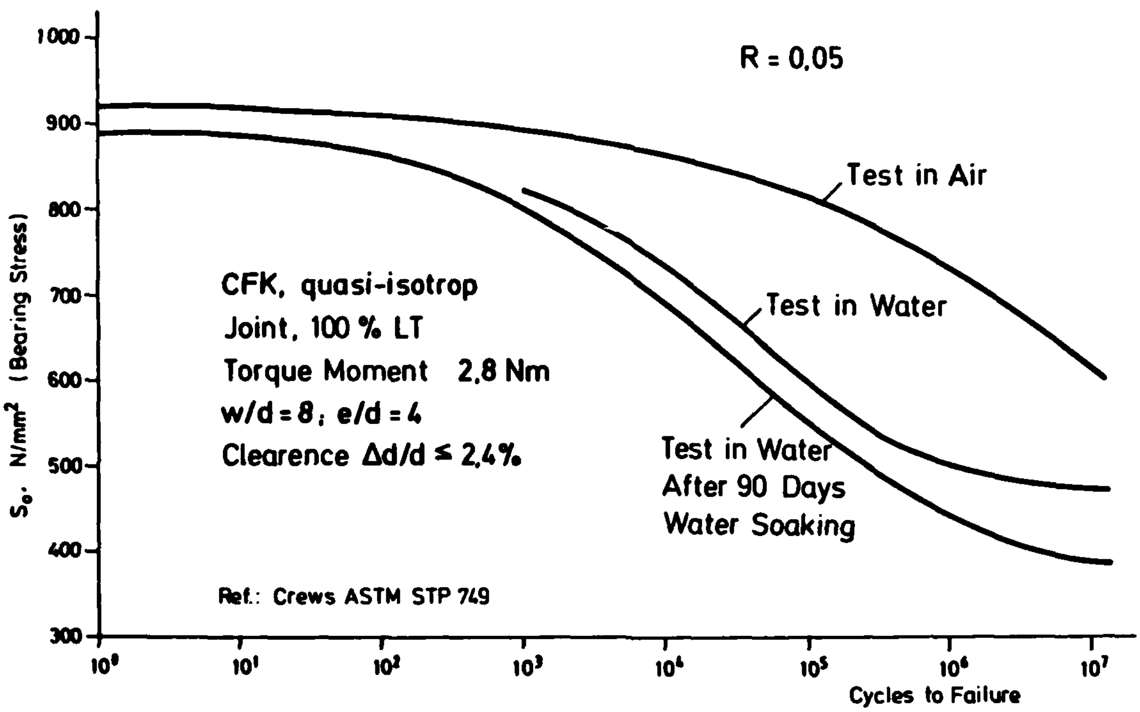

| LBF | Increase in Deformation During Fatigue Loading, R = - 1.66 [1] | Fig. 5 |
|---|---|---|

| Design Parameter | Influence on | | | Investigation |
|---|---|---|---|---|
| | Static Strength | Fatigue Strength | Increase of Deformation During Fatigue Loading | |
| Clearance → Interference Fit | Higher | Higher | Retarded | Garret, Kam, Gerharz-Schütz |
| Increase in Torque Moment | Higher | Higher | Retarded | Godwin, Kong, Crews, Collings, Gerharz |
| Higher Number of Fasteners | Higher | Higher | Retarded | Ramkumar, Hyer-Perry-Lightfoot, Gerharz-Schütz |
| Single Shear → Double Shear | Higher | | Retarded | Agarwal Hart-Smith, Gerharz-Schütz |
| Reinforcement | Improvement somewhat Lower than Increase in Section | | Retarded | Gerharz-Schütz |
| Higher Local Deformation at Fastener | Higher | ? | ? | Eisenmann |

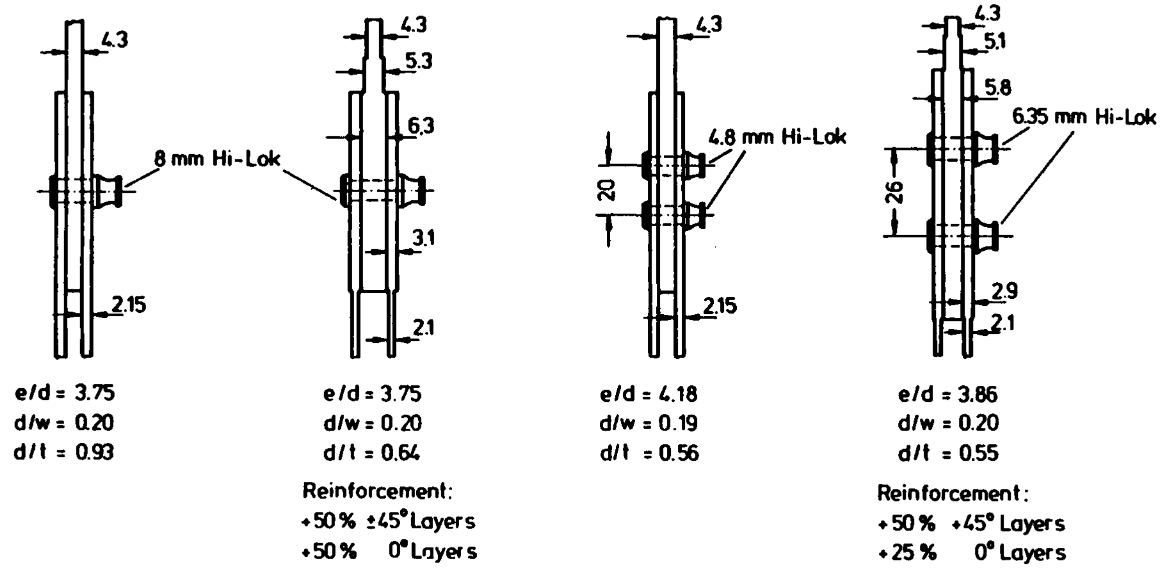
Influence of Design Parameters on the Strength Behaviour of Bolted CFRP-Joints Fig. 6

| Environment Parameter | Typ of Joint | Influence on | | | Investigation |
|---|---|---|---|---|---|
| | | Static Strength | Fatigue Strength | Increase in Deformation | |
| High Temperature During Loading | 100% Load Transfer | Same Decrease as in Undisturbed Region (Tension) | ? | ? | Kong, Wilson |
| - Aging with Moisture<br>- Temperature Changes (Thermal Spike) | 100% Load Transfer | at 90° C 20% Decrease (Tension) | ? | ? | Wilkins |
| - Loading in Water<br>- Preconditioning in Water | 100% Load Transfer | no influence (Tension) | 40 % Decrease at $N_B = 10^6$, $R = 0$ | Rapid | Crews |
| - Aging with Moisture with and without Temperature Changes | 0% Load Transfer | no influence (Tension) | ? | ? | Wilkins |
| | | at 1.2 % FG - 20 % Decrease (Compression) | | | Shyprykevich |

Influence of Environment Parameters on the Strength Behaviour of Bolted CFRP Joints Fig. 7




Influence of Water on the Fatigue Strength of a Composite Joint Fig. 8

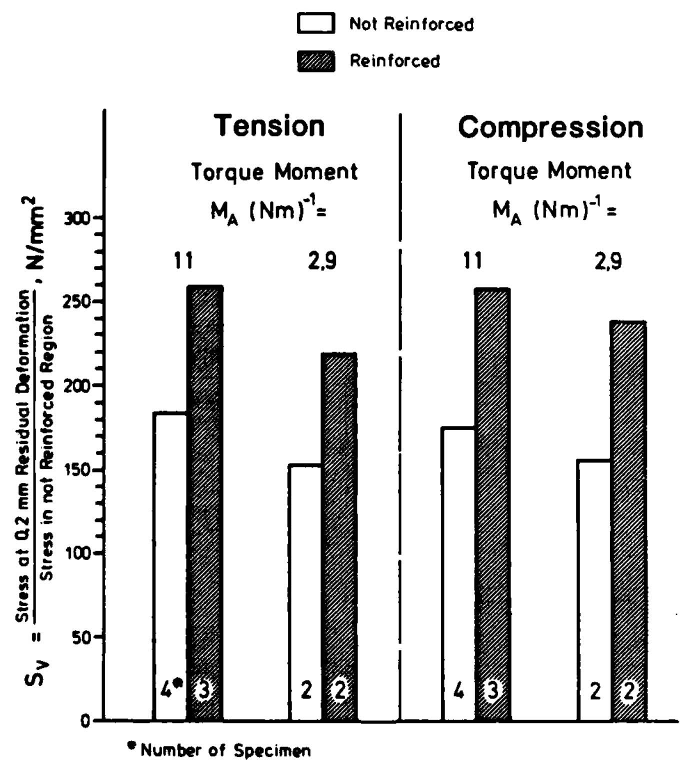



Laminate, 4.3 mm Plate: $[(0_2/\pm45/0_2/\pm45)_2 90]_s$; 2.15 mm Plate: $[0_2/\pm45/0_2/\pm45/\overline{90}]_s$

Fibertype: T 300; Matrix 914 C

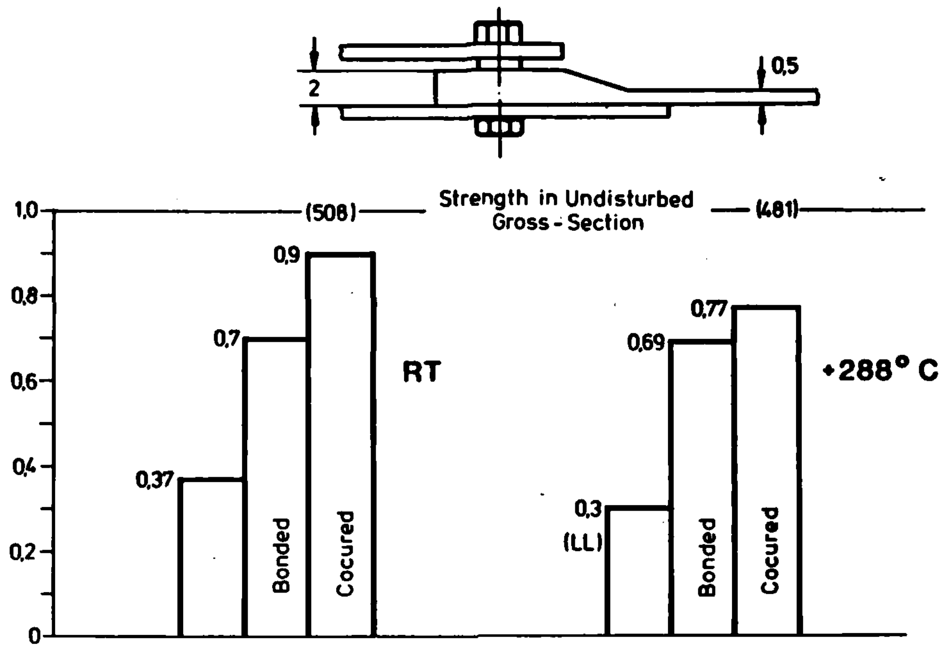
Bolted CFK-CFK Joints With and Without Reinforcement

Fig. 9

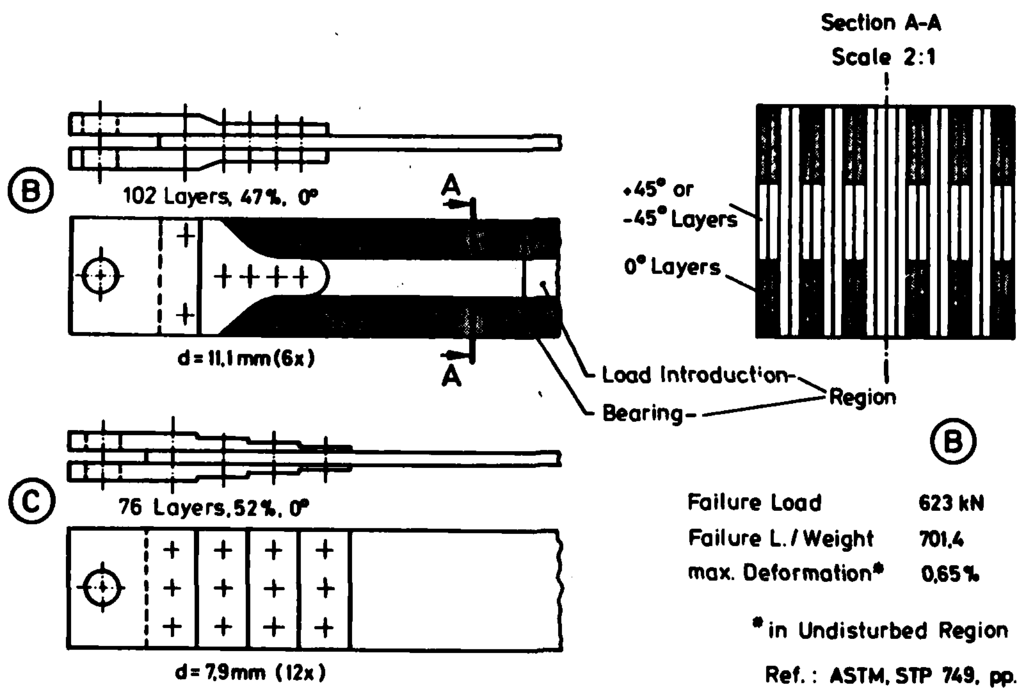



Influence of a Local Reinforcement on the Strength of CFRP Joints with 100% Load Transfer (High and Low Torque Moment of Bolt)

Fig 10




**Strength of Joint with Bonded and Cocured Doubler**
**(Increase of Section by Factor of Four)**
**Celion 3000/PMR-15, Quasi-Isotrop, Ref.: NASA CR 165955** Fig. 11

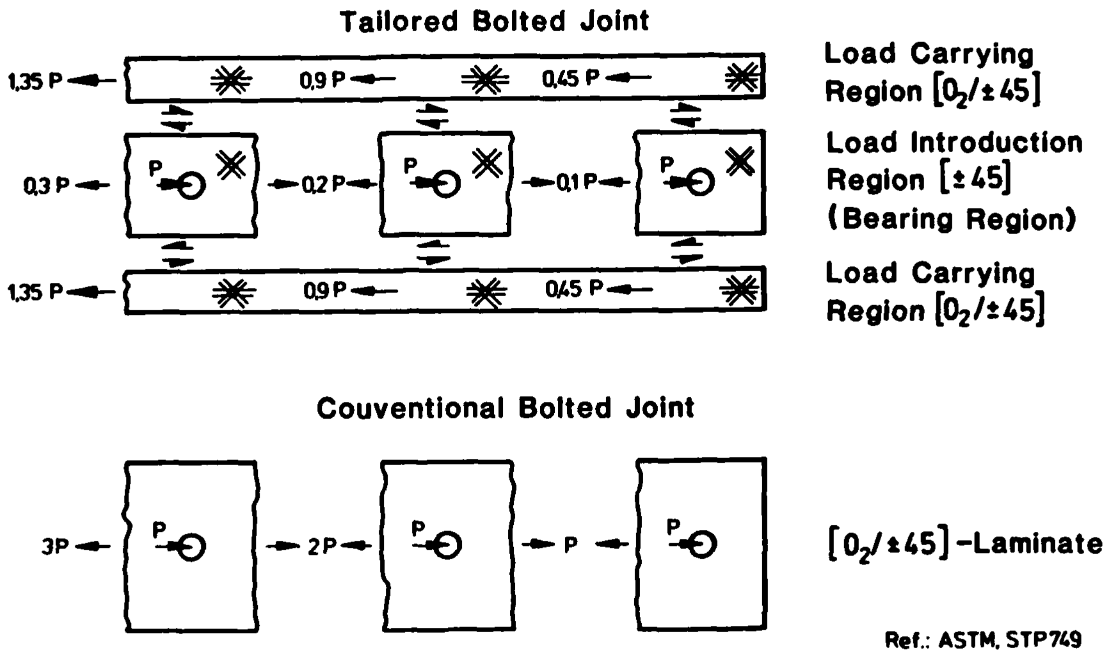



| | B | C |
|---|---|---|
| Failure Load | 623 kN | 333,6 kN |
| Failure L./Weight | 701,4 | 559,3 |
| max. Deformation* | 0,65% | 0,37% |

* in Undisturbed Region

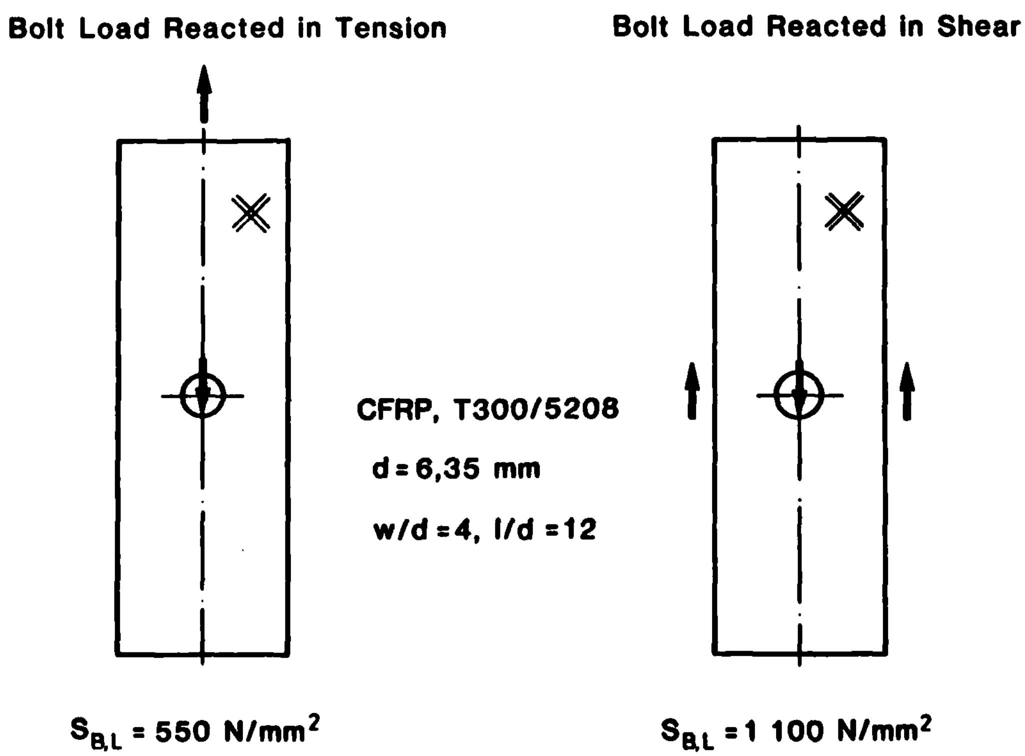
Ref.: ASTM, STP 749, pp.117

**Influence of an Increase of Local Flexibility**
**on Bearing Strength (Softening)** Fig. 12




**Laminate Tailoring alters internal Load Paths in a Multifastener Joint**

Fig. 13




**Dependance of Bearing Strength on Load Path**

Fig. 14

# BOLTED JOINTS IN CARBON FIBRE COMPOSITES

by

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## 1 INTRODUCTION

There have been two research programmes carried out at BAe Woodford into the strengths of bolted joints in CFC composites.

Both programmes consisted of theoretical analyses using finite element methods in order to determine stress concentrations and failure levels, and static experimental testing of plain fasteners in double shear. The second programme included some testing of countersunk specimens in single shear and experimental strain analysis using laser-Moire fringe interferometry and acoustic emission monitoring in order to provide an experimental comparison with the theoretical results.

## 2 FIRST PROGRAMME

The work performed in the first programme consisted of a linear finite element analysis, which predicted the stress concentrations at the hole edge. It was hoped to verify the stress concentrations by experimental strain gauge measurement, but it was found that the gauge length was too long to monitor the large stress gradients around the hole edge successfully. It was therefore recommended that a technique such as Moire interferometry was used.

A large experimental test programme was carried out, in which all the tests were performed on plain bolt specimens in double shear. The material used was 130SC/10,000 fibre and Code 69 resin. The aim of the work was to produce laminate characterisation curves, ie curves of the bearing stress at failure plotted against either the w/d ratio or the e/d ratio. (The w/d ratio is the specimen width or bolt pitch against the hole diameter and the e/d ratio is the hole to edge distance against the diameter).

The laminate lay-ups were:

1) 2/3 at 0°, 1/3 at ±45°
2) ±45°
3) $\bar{0}$°
4) 2/3 at 0°, 1/3 at 60°
5) 1/3 at 0°, 2/3 at ±45°

and these were tested with the load applied along the 0° fibres, and at the following angles to the 0° fibres: 22½°, 45°, 67½° and 90°.

Bearing strength at failure was in the range 800MPa to 900MPa, with the ±45° lay-up giving the highest bearing strength.

There were areas, in both the initial experimental and the theoretical work programmes, where the knowledge gained was incomplete or where useful or logical extensions of the work became apparent. These were:

1) Experimental and theoretical investigation on the effect of bolt fit.

2) Experimental work on the strengths of countersunk bolted joints.

3) More detailed stress concentration work together with experimental verification of theoretical results.

4) Theoretical prediction of failure using the finite element analysis.

5) The use of acoustic emission monitoring to determine the first 0° fibre failure and hence the stress concentration.

## 3 SECOND PROGRAMME

The second programme followed up these recommendations and investigated further areas of interest.

The theoretical work used a finite element mesh similar to that in the previous programme, and incorporated a computer program containing polynomials corresponding to the stress-strain behaviour of a carbon fibre composite. Using this method the non-linearity of the material was modelled. The results of the theoretical work were in the form of stress concentration contour plots (Figure 1), displacement contour plots (Figure 2) and failure predictions.

The displacement contour plots were produced to enable direct comparison with the results of the experimental laser-Moire fringe interferometry (Figure 3). This comparison showed good qualitative agreement for both models tested, which were 2/3 at 0°, 1/3 at ±45° and ±45° lay-ups. In the case of the 2/3 at 0°, 1/3 at ±45° there was also good quantitative agreement.

Failure prediction was made by applying a criterion that failure occurred when the strain in any fibre of the model reached 12,000 microstrain. This gave a failure load of 9.75kN in one of the models analysed, whereas the experimental failure load was 15.12kN. However, the first 0° fibre failure occurred at 9.18kN from the results of the acoustic emission monitoring, and this result validates the theoretical work. Clearly if an accurate failure prediction is to be made, then a more complex failure criterion is required than the simplistic 'strain to failure'.

The materials used for the second experimental programme were XAS fibre with BSL-914 resin and these were laminated to give 3mm thick specimens. The bolt sizes used were 6.35mm and 4.83mm and the bolts were standard close tolerance steel pins.

There were four major parts of the experimental programme:

1) An investigation into the effect of ply stacking sequence on the bearing strength of joints.

2) The effect of countersunk head fasteners on the failure strengths of bolted joints.

3) A series of tests to produce laminate characterisation curves.

4) Experimental verification of theoretical results.

### 3.1 Ply Stacking Sequence

The investigation into the effect of ply stacking sequence was performed on three different sequences within a 2/3 at 0°, 1/3 at ±45° lay-up: a homogenous laminate in which the plies of the same orientation were distributed, a stratified laminate where plies of the same orientation were stacked together, and a semi-stratified laminate in which the ply distribution was midway between that in the homogenous and the stratified. The results of this investigation showed a decrease in the failure strength of the specimens with increasing stratification. (Figure 4).

### 3.2 Countersunk Fasteners

Some problems were encountered in the testing of the countersunk specimens. It was originally intended to use a 6.35mm 100° fastener, but it was felt that this fastener would be unsuitable as the depth of the countersink was close to the laminate thickness. A 4.83mm titanium fastener was used as a replacement. This fastener proved unsatisfactory in this high load transfer application and failed in a shear/bolt bending mode where the thread entered the block. Two specimens were tested with a 6.35mm 100° countersunk fastener; in one test the specimen failed, in the other the fastener failed by pulling off the head. The problem was overcome by manufacturing special loading studs (Figure 5) from high tensile steel, and testing the specimen with the countersink inwards (Figure 6). Using this method, results were obtained enabling laminate characterisation curves to be drawn for the three lay-ups tested (Figure 7); these were:

1) 2/3 at 0°, 1/3 at ±45°
2) 1/3 at 0°, 2/3 at ±45°
3) ±45°

The specimens were tested in pairs in order to minimise the effect of bending, which could have caused premature failure.

### 3.3 Laminate Characterisation

The laminate characterisation work per se was carried out on three different lay-ups, using two bolt diameters, which were 6.35mm and 4.23mm. The specimens were tested in double shear using plain fasteners. The results showed the maximum bearing strength at failure was achieved in the 1/3 at 0°, 2/3 at ±45° laminate at 1080MPa. There was an increase of approximately 4% from the 6.35mm to the 4.83mm fastener (Figure 8).

3.4 Experimental Verification

Experimental strain analysis was performed using laser-Moire fringe interferometry; this method gives fringe patterns representing the in-plane displacements of the specimen. Briefly the method of the work is to:

1) Apply a photo-resistive coating to the surface of the specimen

2) Mount the specimen in the test machine and expose it to the laser, which has been collimated, and this produces a horizontal and transverse grating on the photo-resist.

3) Develop the photo-resist to 'etch' the grating

4) Replace the specimen in the test machine in the same position as previously and re-expose to the laser grating

5) Load the specimen; the grating on its surface distorts and an interference pattern is produced.

The results of this work were compared with theoretically produced displacement plots, and in the particular case of the 2/3 at 0°, 1/3 at ± 45° laminate, experimental strains of 1373 microstrain were recorded and theoretical strains of 1315 micro-strain were predicted at the same position. In general, however, there was considerable scatter between the theoretical and experimental results.
The agreement was considerably better than that obtained in the earlier experimental strain analysis using strain gauges. There are obvious problems associated with working in areas of high strain gradients, and the results of the laser-Moire fringe work are very promising.

Acoustic emission monitoring was used in order to determine the load at which the first 0° fibre failed, assuming this to be at the hole edge. The stress concentrations were calculated, and then compared with those theoretically derived. Those determined experimentally were approximately twice the theoretical values.

4 FURTHER WORK

Following the work performed in this second programme a further programme of work is being considered. The areas for investigation are both theoretical and experimental. The theoretical work is intended to model the bolt behaviour and the load distribution to produce an accurate prediction of failure and to model multi-bolt joints. The experimental work will consist of:

1) Laser-Moire fringe interferometry on specimens of different lay-ups and bolt types

2) Testing of specimens with off-axis loading, ie using a non-zero loading angle with respect to the 0° fibre direction

3) A small programme of bolted joints in composites of improved toughness, ie using a tougher resin system than the present epoxy systems.

4) Observation of the growth of delamination due to the bolt loading. It is intended that the specimen will be loaded up to a percentage of the expected failure load, unloaded, and examined using ultrasonic techniques. This will be repeated at a number of loads until failure.

5) An investigation of countersunk joints in single shear. This is the major part of the experimental work as most joints in aircraft are of this type. The basic specimens are to be tested singly and in single shear to allow bolt rotation, using the bolt bearing extensometer to determine bearing deflection, but testing and examination of the multi-bolt row joint case will also be included. The areas which are considered to be important are:

   a) What effect the relationship between the laminate thickness and that of the attaching structure has on the failure level.

   b) How the depth of the countersink affects the failure mode and mechanism of the specimen.

   c) How the shear-bearing and tensile-bearing interaction varies with the e/d and w/d ratios.

5 ACKNOWLEDGEMENT

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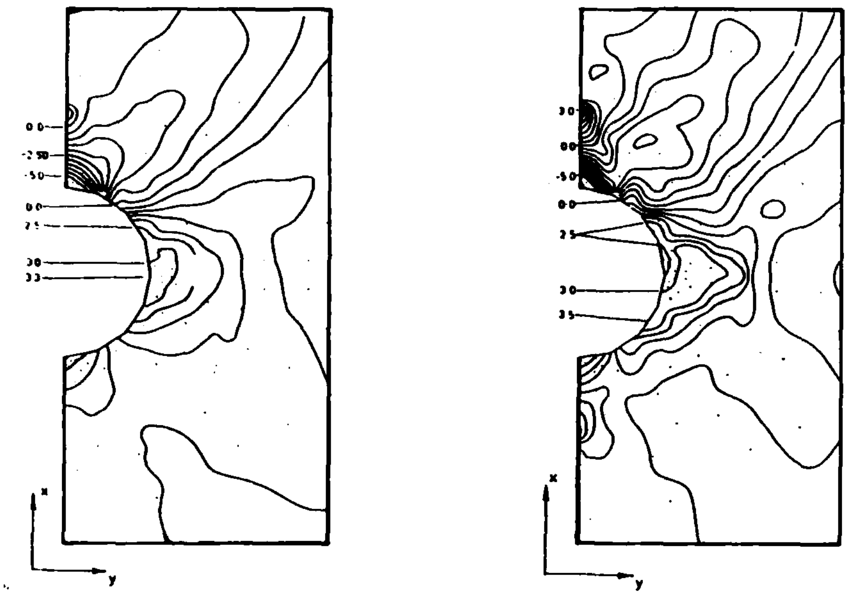
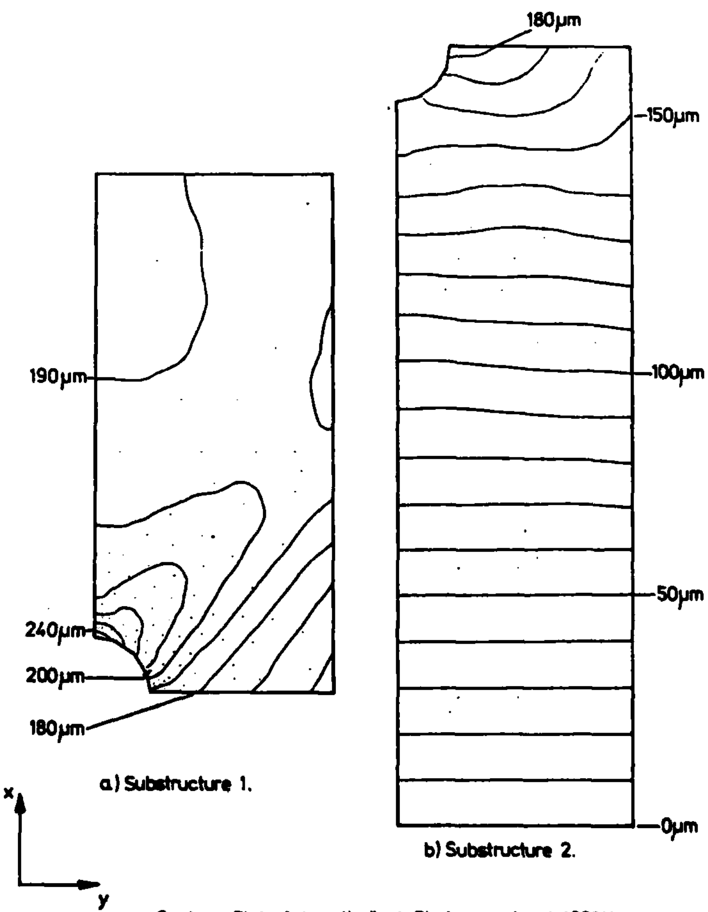



Enlarged Longitudinal Stress Concentration Factor ($K_1$) Contour Plot for Model G209E (±45°) at 16000N Applied Load Linear Analysis

Enlarged Longitudinal Stress Concentration Factor ($K_1$) Contour Plot for Model G209E (±45°) at 16000N Applied Load Non-Linear Analysis

Fig 1



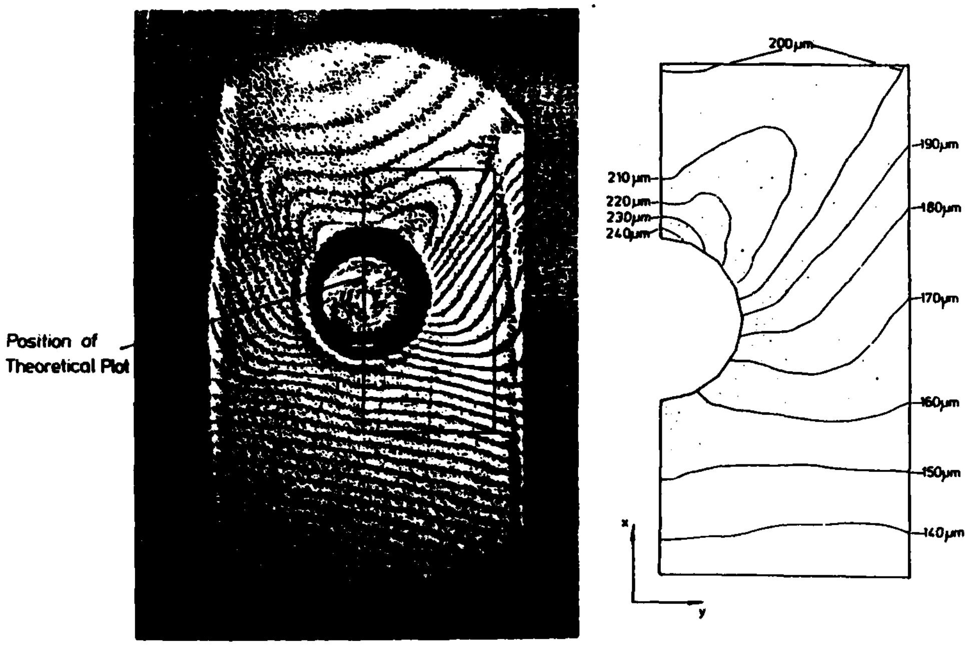

a) Substructure 1.

b) Substructure 2.

Contour Plot of Longitudinal Displacements at 4000N Applied Load (25% of Ultimate Failure Load) Model G209E (±45°)

Fig 2

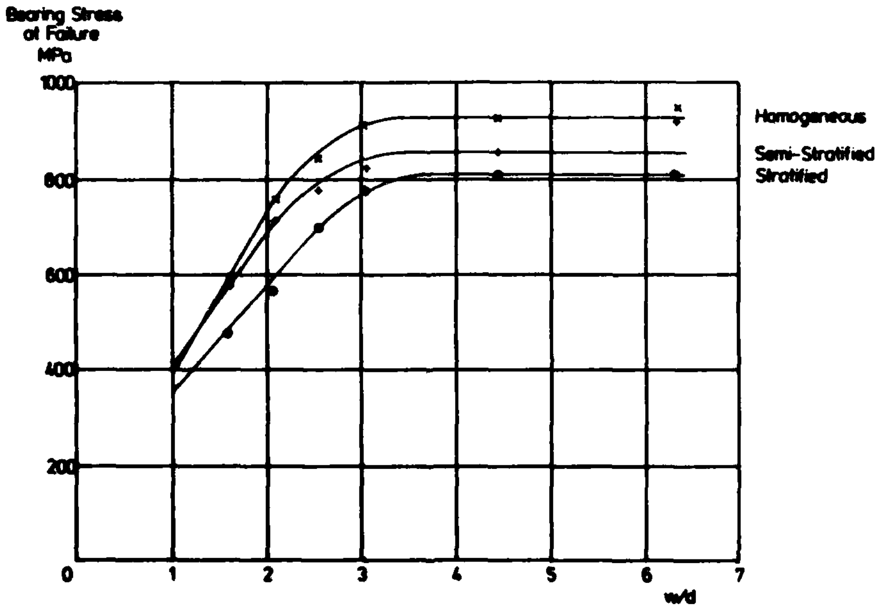
DISPLACEMENT PLOTS




Experimentally Determined

Theoretically Determined

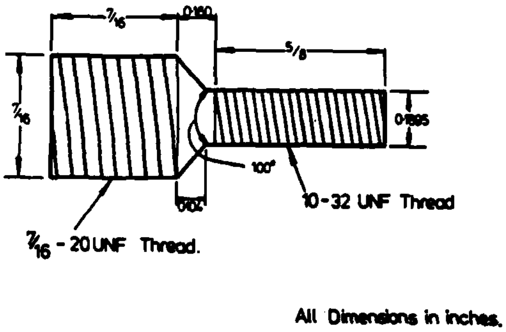
Fig 3




Graph of Bearing Stress at Failure against w/d Ratio

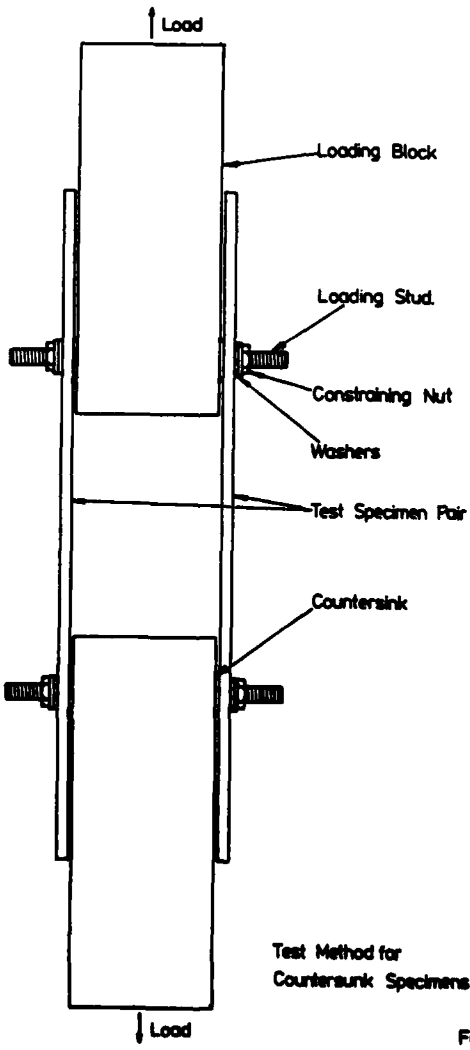
⅔ at 0° ⅓ at ±45° Lay up. Various Stacking Sequences.

Fig 4



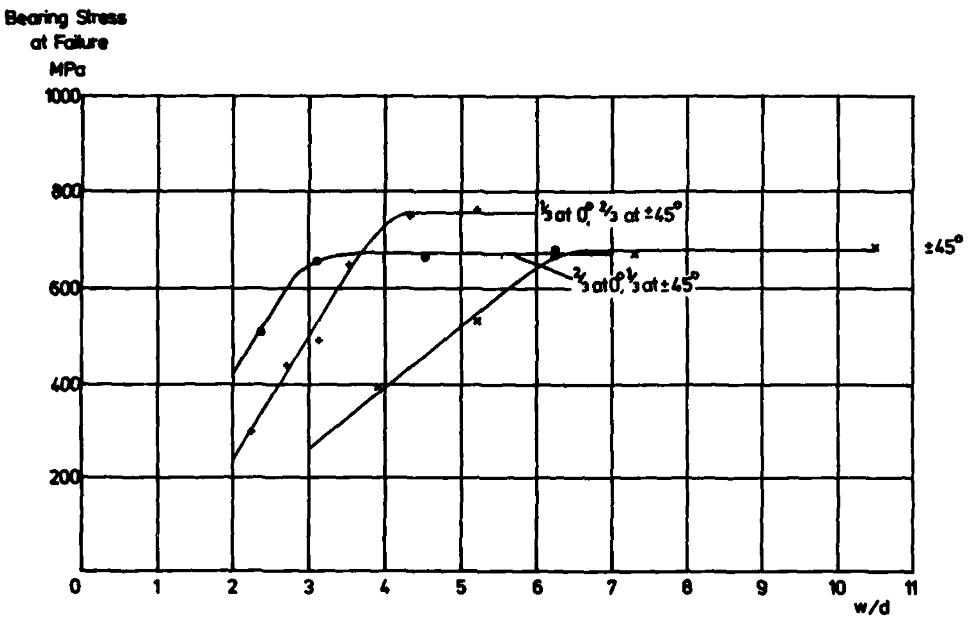

Drawing of Steel (S99) Loading Studs for the Testing of Countersunk Specimens

Fig 5




Test Method for Countersunk Specimens.

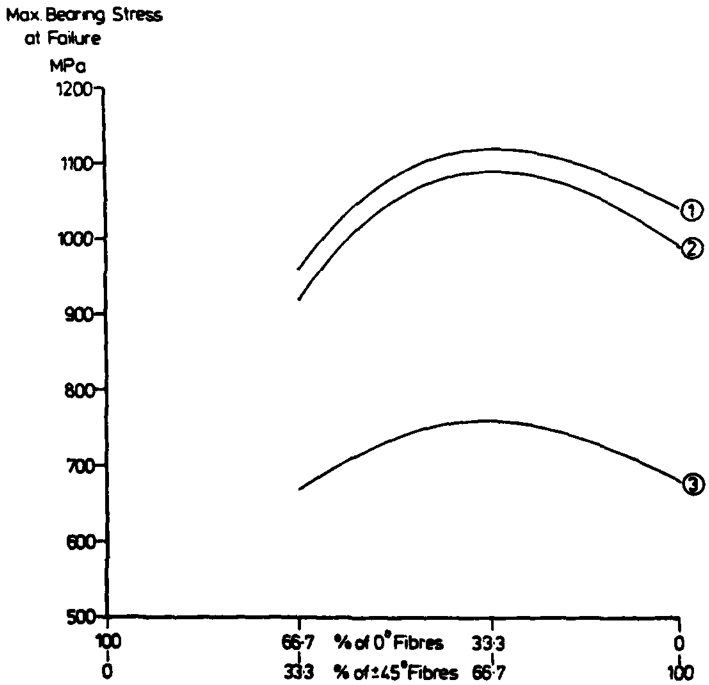
Fig 6




Graph of Bearing Stress at Failure against w/d Ratio for Countersunk Specimens.

Fig 7

The Effect of Lay-up Variation on the Maximum
*Bearing Stress at Failure.*




① 4·83mm Dia. Plain Head Fastener.
② 6·35mm Dia. Plain Head Fastener
③ 4·83mm Dia. Countersunk Head Fastener

Fig 8

# DESIGN OF BOLTED JOINTS
# IN C.F.R.P. STRUCTURES UNDER TENSION

by Pierre LAFON
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This paper concerns the philosophy of AEROSPATIALE Aircraft Division on this subject, and the means they use in C.F.R.P. dimensioning at the industrial scale.

## 1- GENERAL REMARKS :

To-day, the bolted joint is the most common way of assembling composite structures. The use of this type of design leads to considering two evident facts :

- a hole in C.F.R.P. due to a bolt involves a high decrease in strength,
- if the bolt is loaded, this decrease is even more important.

Therefore, bolted joints are critical features in composite structures and their design requires constant attention.

## 2- DESIGN CRITERIA BASIS :

From coupon or element tests, we have two means of analysis :

- empiric rule : translating test results directly by means of simple formulas
- local Finite Element Analysis : using a typical model (Fig. 1), HILL criterion (Ref. 1) and Average Stress philosophy (Ref. 2).

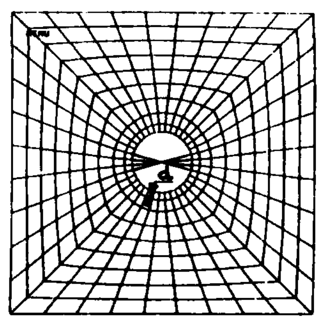


Fig. 1

LOCAL FINITE ELEMENT MODEL
- The radius simulates contact between bolt and plate in compression only.
- d : width of F.E. first line from hole edge.

## 3- UNLOADED BOLT CASE :

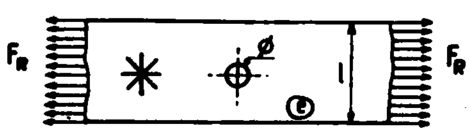


Fig. 2

UNLOADED BOLT CASE

$F_R$ = failure load
e = thickness
$\varnothing$ = bolt diameter
$*$ = lay-up

### 3.1- Empiric rule :

The failure occurs when

$$\sigma^T = k^T \cdot \sigma_R$$

with :

$\sigma_R$ = strength of unnotched specimen (stress)
$\sigma^T$ = strength of bolted specimen (stress in net section)

$$\sigma_T = \frac{F_R}{e\,(l - \varnothing)}$$

$k^T$ = hole factor mainly depends on hole size and lay-up

### 3.2- Local F.E. analysis :

This analysis is done with design strength values.
With the current variability and the number of specimens tested, the objective is to have :

$$\frac{\text{test results}}{\text{analysis}} \# 1{,}25$$

This target is reached with d = 1 mm (d : width of F.E. first line from hole edge (see Fig. 1).

## 4- LOADED BOLT CASE :

### 4.1- Empiric rule :

By comparison with the previous tests (unloaded case) the empiric rule becomes :

Failure occurs when :

$$\sigma^T + km.\ \sigma m = k^T.\ \sigma_R$$

with :

$$.\ \sigma^T = \frac{F_3}{e\,(l - \varnothing)}$$

$$.\ \sigma m = \frac{F_2}{e\ .\ \varnothing}$$

(bearing stress)

( ) Failures values

. km : bearing factor

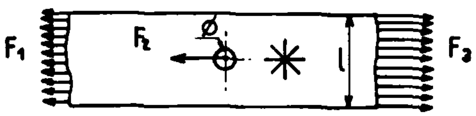


Fig. 3

LOADED BOLT CASE

$F_3$ = failure load
$F_2$ = bearing force

For the other parameters, see Fig. 2.

### 4.2- Local F.E. analysis :

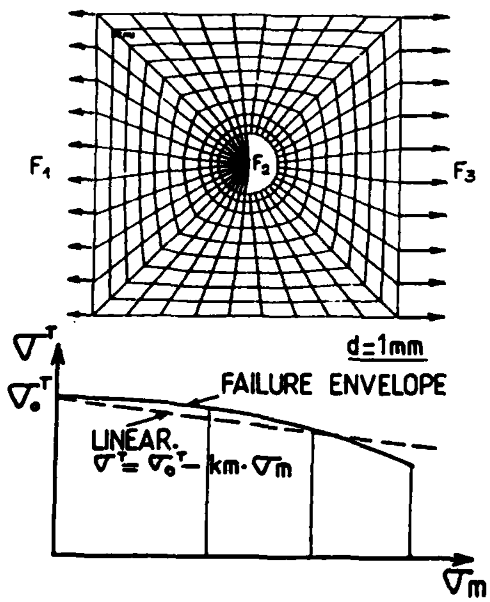


Fig. 4

LOADED BOLT CASE

The bearing effect is studied by the use of the local F.E. model previously defined (d = 1 mm)

The decrease in strength due to bearing is given on Fig. 4. On the same scheme, the linear empiric rule of § 4.1 is plotted.

There is a good correlation between the two analyses up to $\sigma m$ = 250-300 MPa for the specimen tested.

## 5- USE OF DESIGN CRITERIA :

### 5.1- Empiric rule :

In the most simple cases, we use the empiric rule, in particular when the bolt load and general loading are in the same direction (Fig. 5)

$$\sigma^T + km \cdot \sigma m = k^T \cdot \sigma_R$$

with $l$, typical width = 5 Ø

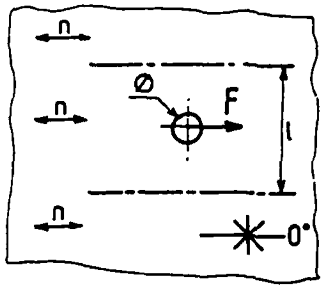


Fig. 5

### 5.2- Local F.E. analysis :

In more intricate cases (Fig. 6), the use of the previously defined local F.E. model is necessary. This model is limited by a 5 Ø x 5 Ø square as shown on Fig. 7.

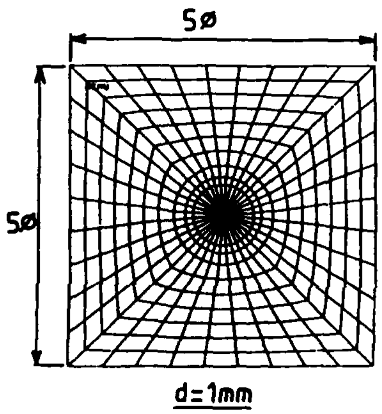


Fig. 7

LOCAL F.E. MODEL

d = 1 mm
(width of F.E. first line from hole edge)

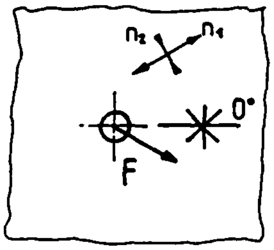


Fig. 6

n, $n_1$, $n_2$ : loading flux

Comment :

To determine the true contact points between bolt and plate, an iterative analysis is necessary and this method is therefore more expensive than the empiric one.

## 6- APPLICATION TO REAL LAP JOINTS : (Use of empiric rule)

The following two examples are analysed by the use of the empiric rule.

### 6.1- First example :

The T300-N5208 specimen is defined on Fig. 8.
The design strength ($F_R$ = 669000 N) is established from design data :

- unnotched strength : $\sigma_R$ = 580 MPa
- hole factor : $k^T$ = 0,5
- bearing factor : km = 0,25

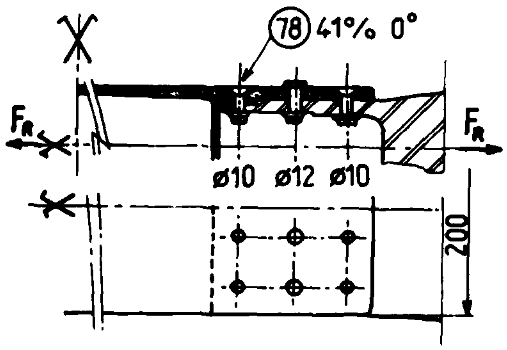


Fig. 8

FIRST EXAMPLE SPECIMEN

6.2- Second example :

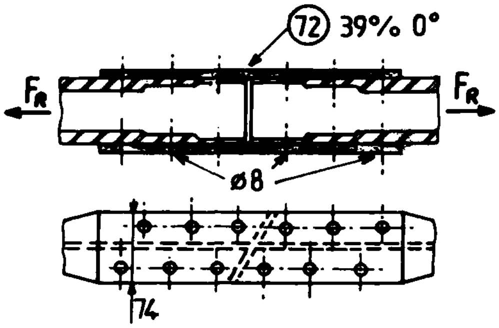


Fig. 9

SECOND EXAMPLE SPECIMEN

The specimen shown on fig. 9 was tested with T300-N5208 and T300-BSL914C.

The design strength ($F_R$ = 211000 N) is consistent with the design data :

- unnotched strength : $\sigma_R$ = 551 MPa
- hole factor : $k_T$ = 0,5
- bearing factor : km = 0,25

6.3- Test results and comparison with design values :

The testing gave the following results :

1st example : (3 specimens)

- 858000 N
- 875000 N
- 911000 N

2nd example : (2 x 2 specimens)

- T300-N5208 (- 280000 N
  (- 260000 N
- T300-BSL 914C (- 293000 N
  (- 300000 N

The comparison between test results and design values is shown on Fig. 10.
It appears that the analysis is perhaps too conservative in these cases.

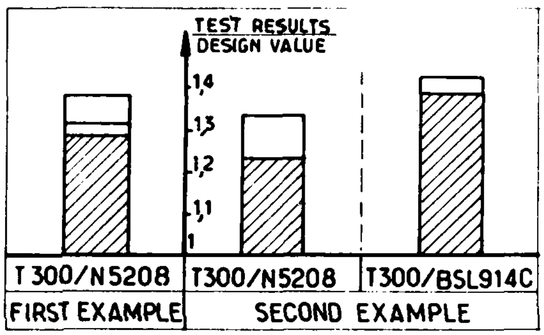


Fig. 10

TEST RESULTS/DESIGN VALUE COMPARISON

7- FATIGUE EFFECTS :

It is generally admitted that the fatigue of a subsonic civil aircraft produces neither significant damage nor static strength decrease in C.F.R.P.
We have partially verified this assumption during fatigue tests, based on the above example 1 specimens. The results of these tests are summarized in the table of Fig. 11.

| FATIGUE LEVEL | RESULTS | COMMENTS |
|---|---|---|
| $\pm$ 0.5 $F_R$ | Test stopped at N = 14300 cycles | - 12% bolt heads broken<br>- 35% bolt heads cracked |
| $\pm$ 0.3 $F_R$ | N = 250 000 cycles | - 30/35% bolt heads cracked |
| $\pm$ 0.25 $F_R$ | | - some small delamination in C.F.R.P. near bolts |

Fig. 11 - FATIGUE TEST RESULTS

The target life was 250 000 cycles and the primary fatigue level selected $\pm$ 0,5 Static Strength, which is higher than the typical fatigue level for subsonic civil aircraft.

When the fatigue was reduced to a more realistic level, the target life was reached and the small damage in C.F.R.P. was only due to cracked bolt heads.

Before residual strength testing, it was necessary to replace the bolts. These tests do not provide significant change in strength. The failure occurs in C.F.R.P. at the first bolt row.

Therefore, these tests confirm that the static weakness is in C.F.R.P. and the main fatigue weakness in bolts or metal parts.

## 8- CONCLUSION AND COMMENTS :

For the design of bolted joints in C.F.R.P., the empiric rule provides suitable results in most cases. In limited cases, when the empiric rule is inapplicable, we use the Local F.E. Analysis which is longer and more expensive.

But the two methods are not fully satisfactory since they ignore several parameters, such as :

- stacking sequence,
- bending of joint components,
- bearing stress variation with thickness

## REFERENCES :

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Ref. 2 : NUISMER R.J. and WHITNEY J.M., "Uniaxial Failure of Composite Laminates Containing Stress Concentration"; Fracture Mechanics of Composite, ASTM STP 593, American Society for Testing and Materials.

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14. Abstract

This publication contains three papers heard by the Structures and Materials Panel Sub-Committee on Mechanically Fastened Joints in Composites. The papers survey the various parameters governing the behaviour of bolted joints, and give some experimental data representative of behaviour under load. It is concluded that poor static strength, rather than good fatigue strength, is a characteristic of this type of joint; a Panel Specialists' Meeting is to review the topic.

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lay-ups, using two bolt diameters, which were 6.35mm and 4.23mm. The specimens were tested in double shear using plain fasteners. The results showed the maximum bearing strength at failure was achieved in the 1/3 at 0°, 2/3 at ±45° laminate at 1080MPa. There was an increase of approximately 4% from the 6.35mm to the 4.83mm fastener (Figure 8).